Molecular Pathways: Mitochondrial Reprogramming in Tumor Progression and Therapy
M. Cecilia Caino and Dario C. Altieri

Abstract

Small-molecule inhibitors of the phosphoinositide 3-kinase (PI3K), Akt, and mTOR pathway currently in the clinic produce a paradoxical reactivation of the pathway they are intended to suppress. Furthermore, fresh experimental evidence with PI3K antagonists in melanoma, glioblastoma, and prostate cancer shows that mitochondrial metabolism drives an elaborate process of tumor adaptation culminating with drug resistance and metastatic competency. This is centered on reprogramming of mitochondrial functions to promote improved cell survival and to fuel the machinery of cell motility and invasion. Key players in these responses are molecular chaperones of the Hsp90 family comprising mitochondrial Hsp90s in preclinical development (gamitrinib) and mitochondrial Hsp90s in preclinical development (gamitrinib) prevents adaptive mitochondrial reprogramming and shows potent antitumor activity in vitro and in vivo. Other therapeutic strategies to target mitochondria for cancer therapy include small-molecule inhibitors of mutant isocitrate dehydrogenase (IDH) IDH1 (AG-120) and IDH2 (AG-221), which opened new therapeutic prospects for patients with high-risk acute myelogenous leukemia (AML). A second approach of mitochondrial therapeutics focuses on agents that elevate toxic ROS levels from a leaky electron transport chain; nevertheless, the clinical experience with these compounds, including a quinone derivative, ARQ 501, and a copper chelator, elesclomol (STA-4783) is limited. In light of this evidence, we discuss how best to target a resurgence of mitochondrial bioenergetics for cancer therapy.

Background

Rewiring of mitochondrial function in tumors

Unlike normal cells that oxidize pyruvate in the mitochondrial respiratory chain to produce bioenergy (ATP), tumors rely on a "fermentative", glycolytic metabolism that converts glucose to pyruvate and then lactate in the cytosol, irrespective of oxygen availability (1). Recognized almost a century ago, this "Warburg effect" is now considered a hallmark of cancer (2), independent of stage or genetic makeup. Why tumors with their high biosynthetic needs rely on an energetically inefficient metabolism is not entirely clear. However, the role of glycolysis in generation of biomass to support cell proliferation (1), dampening the production of toxic ROS from mitochondria (3), and adaptation to a hypoxic microenvironment (4), have all been implicated as drivers of metabolic rewiring.

This compounds additional evidence that, at least in certain tumors, disabling mitochondrial respiration favors disease progression. Accordingly, loss-of-function mutations in oxidative phosphorylation genes produce a pro-oncogenic, pseudo-hypoxic state (5), inactivation of tumor suppressors, for instance p53 (6), or activating mutations in the Ras oncogene (7) stimulates glycolysis at the expense of oxidative phosphorylation, and stabilization of HIF1, a master regulator of oxygen homeostasis, dampens mitochondrial respiration to promote glycolysis (8). Irrespective, a rewired tumor metabolism is clearly important for disease outcome, conferring aggressive traits of metastatic competency and drug resistance (4). Not surprisingly, based on these findings, mitochondrial function has been dubbed as a "tumor suppressor" (9), restoring oxidative phosphorylation was proposed as a therapeutic target (10), and agents that inhibit glycolysis have entered clinical testing in cancer patients (see below).

On the other hand, the dichotomy between glycolysis and oxidative phosphorylation in cancer bioenergetics may not be as rigid as previously thought. In fact, we know that mitochondria remain fully functional in most tumors (11), oxidative phosphorylation still accounts for a large fraction of ATP produced in cancer (12), and even under conditions of severe hypoxia, cytochromes are fully oxidized to support cellular respiration (13). This biochemical evidence fits well with a flurry of functional data that point to oxidative phosphorylation as an important cancer driver (Table 1). Accordingly, mitochondrial respiration contributes to oncogene-dependent transformation (14) and metabolic reprogramming (15), supports energy-intensive mechanisms of protein translation in tumors (16), maintains cancer "stemness" (17), favors malignant repopulation after oncogene ablation (18), and promotes the emergence of drug resistance (ref. 19; Table 1 summarizes the mitochondrial pathways involved in cancer and the effect of targeting such pathways). In addition, there is evidence that oxidative phosphorylation may be required to support tumor metastasis (5), implicating mitochondrial phosphorylation in cell motility. An inhibitor of mitochondrial Hsp90s in preclinical development (gamitrinib) prevents adaptive mitochondrial reprogramming and shows potent antitumor activity in vitro and in vivo. Other therapeutic strategies to target mitochondria for cancer therapy include small-molecule inhibitors of mutant isocitrate dehydrogenase (IDH) IDH1 (AG-120) and IDH2 (AG-221), which opened new therapeutic prospects for patients with high-risk acute myelogenous leukemia (AML). A second approach of mitochondrial therapeutics focuses on agents that elevate toxic ROS levels from a leaky electron transport chain; nevertheless, the clinical experience with these compounds, including a quinone derivative, ARQ 501, and a copper chelator, elesclomol (STA-4783) is limited. In light of this evidence, we discuss how best to target a resurgence of mitochondrial bioenergetics for cancer therapy.

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Mitochondrial Control of Tumor Progression

Table 1. Mitochondrial pathways that contribute to cancer

<table>
<thead>
<tr>
<th>Function</th>
<th>Genes/pathway</th>
<th>Targeted by</th>
<th>Effect on tumors</th>
<th>Cancer type</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apoptosis resistance</td>
<td>PDK-dependent metabolic-electrical remodeling involves NFAT, mitochondria ROS and K+ channels Kv1.5</td>
<td>DCA (PDK inhibitor)</td>
<td>xenograft growth by 50%–85% vs. vehicle</td>
<td>Various</td>
<td>10</td>
</tr>
<tr>
<td>Oncogene-dependent</td>
<td>Kras, V12, glutamine metabolism (ALT2, GL5) pentose phosphate pathway (GPI), CIII (Rieske) ROS/ERK</td>
<td>LSL-Kras G12D x TFAM/Flk</td>
<td>Tumor load by 70%–80% vs. Kras alone</td>
<td>Lung</td>
<td>14</td>
</tr>
<tr>
<td>transformation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metabolic reprogramming</td>
<td>c-Myc, miR-23a/b, mitochondrial glutaminase (GLS), glutamine catabolism and transport (ACST2), TCA cycle</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Protein translation</td>
<td>mTORC1/4E-BPs translation of mt-mRNAs (including the components of complex V, mt ribosomal proteins and TFAM)</td>
<td></td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Cancer stemness</td>
<td>IMP2, OxPhos (NDUF53, NDUF57, NDUF3)</td>
<td>IMP2 shRNA</td>
<td>Survival of mice injected with gliomaspheres by 60%–160% (IMP2 sh vs. control sh)</td>
<td>Glioblastoma</td>
<td>17</td>
</tr>
<tr>
<td>Malignant repopulation</td>
<td>Kras, p53, mitochondrial OxPhos, b-oxidation, biogenesis (PGC-1α)</td>
<td>Oligomycin (ETC inhibitor)</td>
<td>Maximal survival of mice bearing repressed tumors by &gt;300%</td>
<td>Pancreatic ductal adenocarcinoma</td>
<td>18</td>
</tr>
<tr>
<td>Drug resistance</td>
<td>HSK4-demethylase (JARDB), mitochondrial OxPhos</td>
<td>Vemurafenib (VE600E Braf inhibitor) + phenformin (biguanide hypoglycemic agent)</td>
<td>Xenograft growth by 50%–60% vs. single vemurafenib</td>
<td>Melanoma</td>
<td>19</td>
</tr>
<tr>
<td>Drug resistance</td>
<td>mHsp90, Akt2 translocation to mitochondria, CypD</td>
<td>BEZ235 (PI3K antagonist) + gaminibin (mHsp90 inhibitor)</td>
<td>Median survival of mice bearing GBM by &gt;40% vs. monotherapy</td>
<td>Glioblastoma</td>
<td>35</td>
</tr>
<tr>
<td>Tumor cell motility</td>
<td>mHsp90, AMPK, mTOR, ULK1/FIP200/FAK</td>
<td>Constitutive active mutant of AMPK or ULK1 expression</td>
<td>Breast cancer metastasis to bone by 80%</td>
<td>Various</td>
<td>20</td>
</tr>
<tr>
<td>Metastasis</td>
<td>PGC-1α, mitochondrial biogenesis, OxPhos</td>
<td>PGC-1α shRNA</td>
<td>Breast cancer metastasis to lung by 60%–80%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: The main mitochondrial functions implicated in cancer are presented along the molecular pathways involved. Where available, the effect of targeting these mitochondrial pathways in tumorigenesis, tumor growth, or metastasis are presented.

Abbreviations: 4E-BPs, eukaryotic translation initiation factor 4E binding proteins; ALT2, mitochondrial alanine aminotransferase; CIII, electron transport chain complex III; GBM, glioblastoma; GLS, glutaminase; GPI, glucose 6-phosphate isomerase; IMP2, insulin-like growth factor 2 mRNA-binding protein 2; PDK, pyruvate dehydrogenase kinase; mTORC1, mammalian target of rapamycin complex 1; NDUF53/7, NADH dehydrogenase (ubiquinone) complex assembly factor 3; NFAT, nuclear factor of activated T cells; OxPhos, oxidative phosphorylation; PGC-1α, peroxisome proliferator-activated receptor gamma coactivator 1-alpha; ROS, reactive oxygen species; TCA, tricarboxylic acid.

Mitochondrial Control of Tumor Progression

A compensatory response promotes survival and maintains a proliferative advantage in genetically disparate tumors, correlating with worse outcome in lung cancer patients. Several groups have recently demonstrated the importance of OxPhos and protein folding in the mitochondria for metastatic dissemination in mouse models. For instance, targeting OxPhos by siRNA knockdown of mHsp90 led to 80% reduction in breast cancer metastasis to bone (20). Furthermore, OxPhos impairment after shRNA silencing of the mitochondrial biomass factor PGC-1α inhibited breast cancer metastasis to the liver by 70% to 90% (21). On the contrary, activation of autophagy by expression of a constitutively active mutant of AMPK or ULK1 impaired lung cancer metastasis to the liver (60%–80% reduction; ref. 20).

Mitochondria and tumor adaptation

Against this more composite backdrop, where tumor metabolism dynamically integrates both glycolysis and oxidative phosphorylation, new evidence has uncovered an unexpected role of mitochondria in tumor adaptation to molecular therapy. We have
known for some time that exposure of tumors to small-molecule inhibitors of the PI3K (24), Akt, and mTOR pathway currently in the clinic produces a paradoxical reactivation of the pathway they are intended to suppress (25–27). What was not known was the impact (if any) of this response on disease behavior. Now, more recent studies demonstrated that molecular therapy with PI3K antagonists induced transient metabolic quiescence with reduced oxygen and glucose consumption rates, while promoting the redistribution of active Akt, mostly Akt2 from cytosol to mitochondria (28). Once in mitochondria, Akt2 readily phosphorylated cyclophilin D (CypD; ref. 28), a structural component of the permeability transition pore (29), resulting in inhibition of apoptosis and treatment resistance (Fig. 1; ref. 28). Indeed, CypD−/− cells reconstituted with a nonphosphorylatable CypD mutant cDNA were sensitized to cell death (40%–50% increase in cell killing compared with control). However, this was not the only adaptive response initiated by PI3K therapy in tumors. In fact, treatment with PI3K antagonists induced extensive morphologic changes in mitochondria of transformed cells, with formation of elongated organelles that infiltrated the cortical cytoskeleton (60%–150% increase in cortical mitochondria compared with control) and localized in proximity of membrane protrusions associated with cell motility (Fig. 1; ref. 30). This process of subcellular mitochondrial trafficking required active oxidative phosphorylation and organelle dynamics, but not ROS production (30). In turn, these repositioned, "cortical" mitochondria provided an efficient, "regional" energy source to fuel the machinery of cell motility, supporting heightened turnover of focal adhesion complexes (150%–300% increase in the rate of formation of new focal adhesion complexes), increased membrane lamellipodia dynamics (30%–50% increase in size of cell protrusions), and enhanced random cell motility. Overall, this culminated with paradoxical increased tumor cell migration (80%–110% increase in speed of migration and 65%–85% increase in distance traveled) and invasion (100%–300% increased two-dimensional invasion of prostate cancer cells; 50%–100% increased invasion of three-dimensional glioblastoma spheroids) after PI3K therapy compared with controls (Fig. 1; ref. 30).
The implications of these findings may be far-reaching. Supported by compelling experimental evidence (31), there have been high expectations that therapeutic targeting of the PI3K pathway could fulfill the goals of "personalized" cancer medicine. The reality in the clinic was different, as these agents showed limited activity, short-lived patient gains, and measurable toxicity (24). The new findings described above (28, 30) may explain, at least in part, this unfavorable outcome, and should caution against the use of PI3K antagonists as monotherapy in the clinic. From a mechanistic standpoint, these results highlight a new, powerful role of mitochondrial metabolic reprogramming in tumor adaptation, modulating treatment response, and paradoxical acquisition of metastatic competency.

Clinical–Translational Advances

Altogether, the reshaped research landscape summarized above points to mitochondria as a hub of tumor responses, and important therapeutic target in cancer (32). This concept has been successfully pursued with the clinical development of modulators of apoptosis, a process regulated at the outer mitochondrial membrane (29). But the idea of targeting mitochondrial metabolism, let alone mechanisms of mitochondrial adaptation for cancer therapeutics, is still in its infancy (32).

Even therapeutic efforts to disable well-established glycolytic pathways in tumors (11, 33, 34) have relied on a relatively small portfolio of drug candidates. As an example, early-stage clinical trials pursued inhibition of hexokinase (HK) isoenzymes, with the goal of preventing the first reaction of glycolysis. One such HK inhibitor in the clinic is lonidamine (TH-070), a derivative of indazole-3-carboxylic acid. A phase II trial in 35 patients with ovarian cancer showed an 80% objective response rate of TH-070 in combination when the drug was administered along with paclitaxel and cisplatin (35). A phase II trial in 31 patients with non–small cell lung cancer who were treated with TH-070 in combination with cisplatin, epipodophyllotoxin, and vindesine showed that 89% of patients had either a partial remission or stable disease (35). Despite these early promising trials, TH-070 development was terminated after disappointing results in two randomized phase III trials (35).

A second agent that prevents glycolysis, 2-deoxyglucose (2-DG), a nonmetabolizable glucose analogue, was also pursued in the clinic. However, dose escalation phase I trials in patients with castrate-resistant prostate cancer and other advanced solid tumors resulted in asymptomatic QTc prolongation that limited further drug evaluation (35).

An independent approach involved therapeutic inhibition of pyruvate dehydrogenase kinase (PDK1) with the small-molecule antagonist dichloroacetate (DCA). PDK1 is a recognized therapeutic target in cancer (36), given its ability to phosphorylate and inhibit the pyruvate dehydrogenase complex (PDC), thus preventing the decarboxylation of pyruvate to Acetyl-CoA and its subsequent entry in the tricarboxylic acid cycle (37). Clinical trials (phase I) with DCA in glioma patients revealed manageable tolerability and hints of objective responses (38). Although a phase II trial of DCA in non–small cell lung cancer was stopped early due to treatment-related deaths and lack of clinical benefit (39), encouraging preclinical results were reported for the combination of DCA plus 5-fluorouracil and cisplatin in gastric cancer (35). DCA is currently being evaluated in patients with head and neck cancer, glioblastoma, and other solid tumors.

Therapeutic strategies to target mitochondria for cancer therapy are at an even earlier stage of development. A promising area is the ongoing development of small-molecule inhibitors of mutant isocitrate dehydrogenase (IDH) isoforms, including IDH2 that localizes to mitochondria. Gain-of-function IDH mutations identified in gliomas (40), acute myelogenous leukemia (AML; 41), and perhaps operative in other cancer types, promote the accumulation of 2-hydroxylutarate (2-HG). This is an oncometabolite that deregulates chromatin remodeling enzymes, resulting in epigenetic silencing of tumor suppressor loci and differentiation block in AML (34). Early trials with mutant IDH1 (AG-120) and IDH2 (AG-221) inhibitors produced impressive objective responses in 60% of AML patients (including complete responses with or without platelet response; ref. 35), opening new therapeutic prospects for high-risk (>60 years of age) AML patients. A second approach to mitochondrial therapeutics focused on agents that elevate toxic ROS levels from a leaky electron transport chain. The clinical experience with these compounds, including a quinone derivative, ARQ 501, and a copper chelator, elesclomol (STA-4783), is limited. In single-agent phase I trials, treatment with ARQ 501 was well tolerated in patients with head and neck cancer and other advanced solid tumors. In a phase II trial in patients with unresectable pancreatic adenocarcinoma, the combination of ARQ 501 and gemcitabine resulted in stable disease in 65% of patients after being on trial for 8 weeks (35). Unfortunately, the early clinical activity of elesclomol in combination with paclitaxel in a randomized phase I trial in melanoma (42), showing more than 200% increase in progression-free survival compared with paclitaxel alone, was not confirmed in a subsequent phase III trial (43).

Against this backdrop, an agent originally designed in our laboratory, gamitrinib (44), may provide a first-in-class, "mitochondriotoxic" activity, conceptually distinct from the above strategies. Gamitrinib was generated to target abundant pools of Hsp90 and its structurally related chaperone, TRAP-1, present in mitochondria, selectively of tumor cells (45). Gamitrinib relies on a combinatorial structure through which the Hsp90 ATPase-inhibitory module of 17-allylamino-17-demethoxygeldanamycin (17-AAG), a first-generation Hsp90 inhibitor, is linked to the mitochondria-targeting moiety of triphenylphosphonium (44). This enables fast and efficient accumulation of gamitrinib in mitochondria, with virtually no inhibition of cytosolic Hsp90, whereas none of the first- or second-generation Hsp90 antagonists currently available in the clinic had the ability to accumulate in mitochondria (44). Because of this cellular selectivity, gamitrinib did not affect known Hsp90 client proteins in the cytosol, for instance, Akt and Chk1 levels, but induced acute mitochondrial dysfunction with depolarization of inner membrane potential and release of cytochrome c in the cytosol, two molecular prerequisites of apoptosis. In contrast, none of the additional derivatives of 17-AAG as well as purine- and isoxazole resorcinol–based Hsp90 antagonists (17-AAG; hydroquinone derivative of 17-AAG, IPI-504; purine analog BIIB021; or isoxazole NVP-AUY922 Hsp90 inhibitors) affected mitochondrial integrity (44). Consistent with these findings, targeting mitochondrial Hsp90s resulted in catastrophic and irreversible collapse of mitochondrial functions (44), disabled complex II–dependent oxidative phosphorylation (22), and induced acute mitochondrial permeability transition (46), producing potent anticancer activity in localized and disseminated
xenograft and genetic tumor models (47). Treatment of mice bearing lung cancer xenografts with gamitrinib produced a 50% to 80% rate of tumor growth inhibition compared with vehicle (44). Gamitrinib combined with TRAIL suppressed the growth of established glioblastomas in mice by 70% to 85% (46). In the Transgenic Adenocarcinoma of the Mouse Prostate (TRAMP) model, gamitrinib prevented the formation of localized prostate tumors of neuroendocrine or adenocarcinoma origin, as well as metastatic prostate cancer to abdominal lymph nodes and liver (47). Intriguingly, targeting the mitochondrial quality control protease, ClpP also produced robust anticancer activity (50% to 60% reduction of xenograft growth) in recent preclinical studies, reinforcing the importance of mitochondrial protein folding in tumor maintenance (23). There is a compelling rationale to think that these organelle-localized chaperones may provide promising targets for cancer therapy. First, their activity likely improves protein folding quality control in mitochondria (48), an ideal mechanism to buffer the risk of proteotoxic stress typical of highly bioenergetically active (tumor) cells. Second, a proteomics screen of mitochondrial molecules that require Hsp90 for folding uncovered key regulators of virtually every organelle function (22), suggesting that disabling this pathway may globally compromise organelle homeostasis. Third, mitochondrial Hsp90 chaperones have been shown to directly sustain tumor cell invasion and metastasis by dampening the activation of autophagy and the unfolded protein response (20).

The preclinical development of gamitrinib in anticipation of human testing is now progressing as an academic endeavor. In addition to general issues of formulation (like its patent compound, 17-AAG, gamitrinib is water-insoluble) and dosing, critical questions of tolerability for normal tissues that are dependent on mitochondrial respiration are of top priority, even though preclinical data have suggested a manageable toxicity profile in mice. Of key relevance are also opportunities for combination therapy with cytotoxics or molecular agents (46). In this context, the unique "mitochondriotoxic" mechanism of action of gamitrinib (44) may be ideally suited to counter therapy-induced tumor adaptation as a driver of disease progression (28, 30). Recent evidence seems to validate this premise, as subtherapeutic concentrations of gamitrinib reversed mitochondrial reprogramming induced by PI3K antagonists, blocked the recruitment of mitochondria to the cortical cytoskeleton in these settings, and suppressed tumor cell invasion (20, 30) and metastasis (47). This may create tangible opportunities for repurposing agents that have shown limited activity in the clinic, as gamitrinib potently synergized with PI3K therapy in a high-throughput drug combination screen, converting a transient, cytostatic effect into potent, cytotoxic anticancer activity (28, 30). In these experiments, the combination of gamitrinib and a PI3K/mTOR inhibitor (BEZ235) extended animal survival in a glioblastoma model (vehicle: median survival = 28.5 days; gamitrinib + PI3K inhibitor: median survival = 40 days; P = 0.003), compared with single-agent treatment (PI3K inhibitor: median survival = 32 days, P = 0.02; gamitrinib: median survival = 35 days, P = 0.008).

Concluding Remarks

Despite a wealth of mechanistic evidence, the exploitation of tumor metabolism for cancer therapy is at an early stage of development. Despite safety concerns for normal tissues, the initial clinical experience with metabolism-modifying drugs has not uncovered major toxicities, confirming the different wiring of metabolic pathways in normal versus transformed cells. A perspective that this process hinges exclusively on glycolysis has been updated by more recent observations that identified a central role of mitochondrial reprogramming in tumor maintenance, drug resistance, and metastatic competency. Together, these findings suggest a more integrated view of tumor metabolism, where glycolysis and oxidative phosphorylation cooperate in a dynamic interplay shaped by the selective pressure of a chronically hypoxic, nutrient-depleted, and therapy-exposed microenvironment. Clearly, this new level of complexity poses fresh challenges to pinpoint which bioenergetics pathway(s) may be most suitable for therapeutic intervention, and further heightens the impact of tumor adaptation as an important barrier to durable responses in the clinic. In this context, agents like gamitrinib that disable broad mechanisms of adaptive mitochondrial reprogramming may open unique therapeutic prospects in drug-resistant tumors, and effectively repurpose otherwise modestly efficacious molecular therapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Authors’ Contributions

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Writing, review, and/or revision of the manuscript: M.C. Caino, D.C. Altieri

Study supervision: D.C. Altieri

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